

Disk emission and absorption lines in LMXB.

Note on the physical conditions of an absorbing material

Agata Różańska¹

¹ N. Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland
E-mail(AR): agata@camk.edu.pl

ABSTRACT

X-ray binaries often show continuum spectrum that is interpreted correctly as emission from an accretion disk. Additionally, two absorption lines from He and H-like iron have been clearly detected in the high-resolution data from several such sources, for instance 4U 1630-472. We show that the continuum X-ray spectrum of 4U 1630-472 with iron absorption lines can be satisfactorily modeled by the spectrum from an accretion disk atmosphere. We performed full radiative transfer calculations using our code ATM21 to model the emission from an accretion disk surface that is seen at different viewing angles. Computed models are then fitted to the high-resolution X-ray spectra of 4U 1630-472 obtained by *Suzaku* satellite. Absorption lines of highly ionized iron originating in a hot accretion-disk atmospheres are important part of the observed line profile, and can be an alternative or complementary explanation to the wind model usually favored for this type of sources.

Next, assuming that absorption lines originate from the wind illuminated by X-ray central source in LMXBs, we can put constraints on the wind location only if we know the volume density number of the absorbing material. There are a few derivations of the distance to the wind in X-ray binaries. We show here, that the density number and wind location agree with density of an upper disk atmosphere at optical depth, $\tau = 2/3$, at the same distance from the black hole. This comparison is done assuming optically thick, geometrically thin standard accretion disk model. Nevertheless, it shows that the wind physical conditions are the same as in thermalized disk gas, and we only have to figure out how the wind is blowing?

KEY WORDS: X-rays: binaries, Stars: individual, Accretion disks, Radiative transfer, Line: profiles

1. LMXBs with absorption lines

The Low Mass X-ray Binaries (LMXBs) are binary accreting systems, where the mass flows onto the neutron star (NS) or the black hole (BH) from the companion. The Secondary is usually main sequence star of the late type K or M that is of the low weight.

When the magnetic field of such a system is negligible, flowing matter with a certain angular momentum can form accretion disk around compact object. According to any global disk models considered for the mass of central object that is close to $10 M_{\odot}$ or less, the effective temperature of the inner radii reaches 10^7 K (Różańska et al. 2011). The temperature at a given radius always increases with the decreasing mass of the central object and with the increasing accretion rate. For such high temperatures of an accretion disk atmosphere, thermal lines from H-like and He-like iron ions are formed, and those lines should be visible between 6.7 to 9.2 keV, where the latter value is the energy of the last iron bound-free transition (from H-like ion to complete ionization). Narrow lines created in the inner disk re-

gion are relativistically smeared, but if they are created far enough, can survive relativistic motion.

Emission from the accretion disk around a compact object is the commonly accepted model for the soft X-ray bump observed in LMXBs. Nevertheless, it is well known that observed X-ray spectra from compact binaries do not always exhibit a disk component. Owing to instrument's technical limits and to spectral state transition, multi-temperature disk component may not be detected in full X-ray energy range. To explain data by the accretion disk emission, we have to be sure that observations were taken when the source was in the so-called "soft state", which is dominated by disk-like component.

Several recently observed X-ray binaries have exhibited absorption lines from highly ionized iron (Borin et al. 2004, Kubota et al. 2007, Miller et al. 2008, Díaz Trigo et al. 2012). Many of those sources show dips in their light curves, which are believed to be caused by obscuration of the central X-ray source by a dense material located at the outer edge of an accretion disk. Such obscuring material was accumulated during the accretion phase from the companion star onto the disk (White &

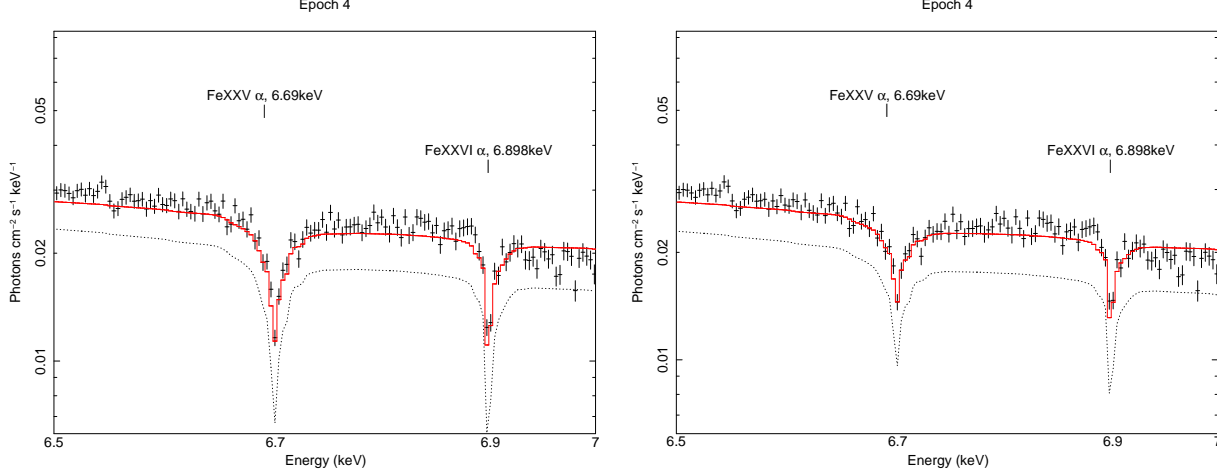


Fig. 1. Focus on the resonant He and H-like iron lines for the fitting done in the 6-9 keV energy range, fitted to the *Suzaku* data of 4U 1630-472. Black crosses show the data, black dotted lines represent the ATM atmospheric model, while red solid lines show the total model. Clearly, complicated line profiles computed in our model, match the observations very well. Left panel shows slightly better fit done for viewing angle $i = 11 \pm 5^\circ$ with $\chi^2/d.o.f. = 1.52$ while right panel shows fit for $i = 70 \pm 6^\circ$ with $\chi^2/d.o.f. = 1.57$

Swank 1982). The presence of dips and the lack of total X-ray eclipses by the companion star indicate that the system is viewed relatively close to edge-on, at an inclination angle in the range $\sim 60 - 80^\circ$ (Frank et al. 1987).

The He-like and H-like Fe absorption features indicate that highly ionized plasma is present in these systems. Study of these lines is extremely important for characterizing the geometry and physical properties of plasma. Recently, it has been shown that the presence of absorption lines is not necessarily related to the viewing angle since non-dipping sources also show those features (Díaz Trigo et al. 2012). Moreover, the FeXXV absorption line was also observed during non-dipping intervals in XB1916-053 (Borin et al. 2004). On the other hand, it was shown by Ponti et al. (2012) that the strength of such lines depends on the spectral state of the X-ray binary. In this paper, we show that such absorption lines can be well fitted by a single disk model, where the line profile is computed taking into account all proper line broadenings (Sec. 2.).

There is a growing number of indications that the density of winds in LMXBs is of the order of 10^{17} cm^{-3} (Díaz Trigo et al. 2013, Miller et al. 2013). Additionally, this wind is located within $r = 10^{10} \text{ cm}$. Below, we calculate vertical disk structure (Różańska et al. 1999) in the way commonly used for studying accretion disk stability curves (Smak 1983, Hameury & Lasota 2005). Assuming that disk is fully thermalized we show how the density number at $\tau = 2/3$ of the disk gas depends on the distance from the central object. We show in Sec. 3., that the observed wind physical conditions (Miller et al. 2013) coincide with density of an accretion disk atmo-

sphere assuming standard geometrically thin, optically thick disk (Shakura & Sunyaev 1973). Conclusions are given in Sec. 4.

2. The case of 4U 1630-472

Recently, we presented fitting of complex continuum and line numerical models to X-ray spectra of 4U 1630-472 (Różańska et al. 2014). In our models, the spectrum of disk emission was obtained from careful radiative transfer computations including Compton scattering on free electrons. The Fe line profiles are computed as the convolution of natural, thermal, and pressure broadening mechanisms. The advantage of our models is that the continuum is fitted with lines simultaneously, which has never been done before in the analysis of X-ray absorption lines seen in LMXBs. The usual procedure is to fit both the disk emission as a standard model in XSPEC fitting package, and Gaussian lines, where the energy of line centroid is a free parameter of fitting. In such a case, lines are usually blue-shifted indicating that absorbing matter outflows.

The accretion-disk atmosphere spectra fit the *Suzaku* data for 4U 1630-472 very well as presented at Fig. 1. The best fit we have obtained for the inclination angle $i = 11^\circ$ - left panel. For higher angles, i.e. $i = 70^\circ$, the fit is just slightly worse - right panel. This angle is within the range of inclination suggested in the literature when taking dipping behavior into account and assuming absorption in the wind. The small difference in fit quality between different inclinations does not allow us to claim constraints on inclination angle.

We modeled continuum and line spectra using a single model. Absorption lines of highly ionized iron can orig-

inate in the upper parts of the disk static atmosphere, which is intrinsically hot because of the high disk temperature. Iron line profiles computed with natural, thermal, and pressure broadening match observations very well (Róžańska et al. 2014).

In this work we do not aim to tightly constrain parameters of the object but rather to show that emission from the accretion disk atmosphere is an important mechanism that gives a vital explanation or at least part of an answer to the question of the origin of iron absorption in X-ray binaries.

The major conclusion of our analysis is that the shape of disk spectrum is interpreted well as 4U 1630-472 emission and that absorption lines do not need to set any velocity shift to explain data. Therefore, the wind explanation for absorbing matter is questionable and not unique. We showed that X-ray data of current quality can be interpreted in several ways, and we cannot easily solve this ambiguity.

3. Connection of the wind with an accretion disk atmosphere

The wind modelling of X-ray absorption has one major difficulty: we need independent volume density measurement to determine the wind location according to the standard formula:

$$\xi = \frac{L_{ion}}{n_0 R^2}, \quad (1)$$

where L_{ion} is the wind ionizing luminosity, n_0 is the hydrogen number density at the wind illuminated surface, and R is the distance of the absorber from an UV/X-ray source, i.e. inner disk, compact object or eventual X-ray corona.

Photoionization models are degenerated, when we assume hard X-ray power-law as the spectral energy distribution (SED) of ionizing source. In such the case, transmitted spectrum from rare more distant cloud looks the same as from dense cloud located close to the center. Therefore, it is not possible to estimate volume density from photoionization calculations for hard power-law X-ray continuum.

Up to now, there are four independent methods of density diagnostic in the wind, but all of them work only in the particular range of parameters: i) variability method (Krolik & Kriss 1995), ii) measurement of the ratio of photoexcitation lines of FeXXII (Mauche et al. 2003) iii) measurement of ionic column densities of the excited metastable states of low ionization ions CII, FeII (Korista et al. 2008), and iv) photoionization modelling valid only if SED is dominated by soft UV/Soft-X-ray component (Róžańska et al. 2008).

In the case of winds in LMXBs, where ionization is very high, the second method is the most suitable, as

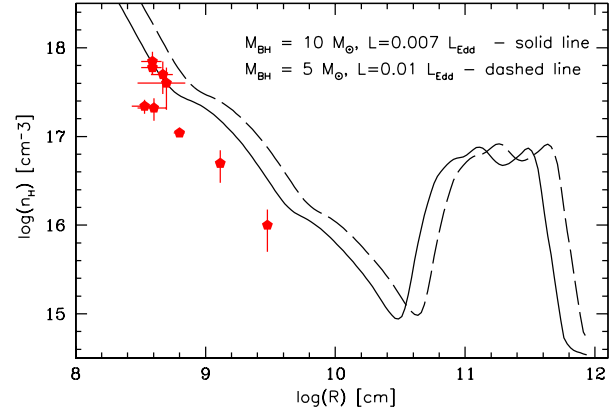


Fig. 2. Number density value at $\tau = 2/3$ in accretion disk around black hole of 10 and 5 Solar masses versus the distance from the black hole. The assumed accretion rates are 0.007 and 0.01 of Eddington accretion rate respectively. The density was calculated using full set of differential equations with parameters given in the text. Points mark the physical parameters of the wind found by Miller et al. 2013 in case of MAXI J1305-704 *Chandra* data. We adopted points from models: 1,2,3,4,5 and 8 fitted to the data and listed in Tab. 5 of this paper.

it was shown recently by Miller et al. (2013) in case of MAXI J1305-704 *Chandra* data. The authors estimated gas density number to be higher than 10^{17} cm^{-3} . Together with the luminosity of the source to be $L = 10^{37} \text{ erg/s}$ and ionization parameter $\log(\xi) = 2.05$, it gives the wind location within $R = 3.9 \times 10^8 - 3 \times 10^9 \text{ cm}$, depending on the fitted model (see Tab. 5 in Miller et al. 2013 paper).

In other sources when excited levels are not detected, with Eq. 1 we can always put upper limit for the density assuming that the wind size is comparable to the distance from an ionizing source. It was done for several objects and summarized at Fig. 1 of paper by Díaz Trigo & Boirin (2013).

In this paper, we made calculations of accretion disk vertical structure solving standard differential equations for 1D fully thermalized gas (Pojmański 1985, Róžańska et al 1999). Such calculations are extensively used to compute time evolution of accretion disk instabilities which explain outbursts presented in optical/X-ray data of accreting compact objects (Smak 1983, Hameury & Lasota 2005).

For our purpose, we calculated vertical structure on different distances from the central black hole of the 5 and 10 Solar masses with accretion rates 0.01 and 0.007 of Eddington unit, respectively. Such accretion rates are used in order to reproduce luminosity used by Miller et al. 2013 for distance determination. Additionally, we assume standard accretion efficiency for non-rotating black hole $1/16$, and viscosity parameter $\alpha = 0.1$. The set of

parameters is very basic, and we are aware that different disk model can change results, but up to know standard disk very well explains observations.

At each distance from the black hole we determined the density number of fully thermalized, i.e. at $\tau = 2/3$, gas. In Fig. 2 we present radial dependence of such density for two cases of black hole masses and accretion rates pointed in the right upper corner. The radiative transfer in those calculations is solved by diffusion approximation, where radiative flux is proportional to the temperature gradient and inversely proportional to the opacity of matter. All visible bumps are due to opacities which are taken to be Rosseland means, but self consistently computed for Solar abundances (Róžańska et al. 1999).

Additionally, several points measured by Miller et al. (2013) are putted on the figure. We have taken models numbered: 1,2,3,4,5, and 8 from their paper listed in Tab. 5. Those points indicate wind physical conditions in MAXI J1305-704 determined by fitting photoionized XSTAR model to the data. The fitting is done on the level where, ionic column densities of photoexited FeXII lines computed in the model are compared with those observed by *Chandra* X-ray telescope.

One can see strong connection of the wind physical parameters with eventual accretion disk atmosphere. This fact may suggest that the wind consist the same material as in upper thermalized disk atmosphere.

4. Discussion

The high density of absorbing matter in LMXBs was first suggested by Frank et al. (1987), who proposed the two-phase medium to explain X-ray observations of such sources. The Authors have concluded that the absorbing material has density number of the order of 10^{16} cm^{-3} for cold phase, and 10^{13} cm^{-3} for hot phase, and it is located within radius of 10^{10} cm .

Up to now, there are only a few sources, where the wind density number was determined from careful spectral fitting (for example Miller et al. 2013), but all of them are showing high values of the wind density around $10^{16-17} \text{ cm}^{-3}$.

Such densities are present in upper thermalized disk atmospheres, within exactly the same distance from black hole as wind location derived from observations. This is a strong argument that the wind can originate from upper parts of the disk slabs, and the only question arises how the wind is blowing? There are several mechanisms proposed as: thermal wind, radiation pressure driven wind or magnetic wind, but none of these processes can be self consistently computed using present computer power. Additionally, to obtain a self-consistent model of radiation pressure winds it is critical to include a more detailed treatment of radiative transfer and ionization in the next generation of hydrodynamic simula-

tions.

The second argument, showing connection of the wind with accretion disk atmospheres is our analyze of 4U 1630-472 *Suzaku* data. All fitted models were computed for high density atmospheres and the line profiles agree with observations. In the wind theory, it is widely accepted that the wind can be launched at the accretion disk surface. Upper layers of atmosphere can become unstable and start to blow material out owing to the radiation pressure. Our analysis does not contradict this fact, but instead shows that absorption at upper atmospheric layers cannot be distinguished from the absorption in the wind, which may be launched in the same region. Data with higher spectral resolution are needed to distinguish between those two models. Future satellites with calorimeters, such as *ASTRO-H* or *Athena+*, will yield the answer.

Acknowledgements

This research was supported by Polish National Science Center grant No. 2011/03/B/ST9/03281. It received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement No.312789.

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